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## POINTING STABILITY OF HINODE AND REQUIREMENTS FOR THE NEXT SOLAR MISSION SOLAR-C

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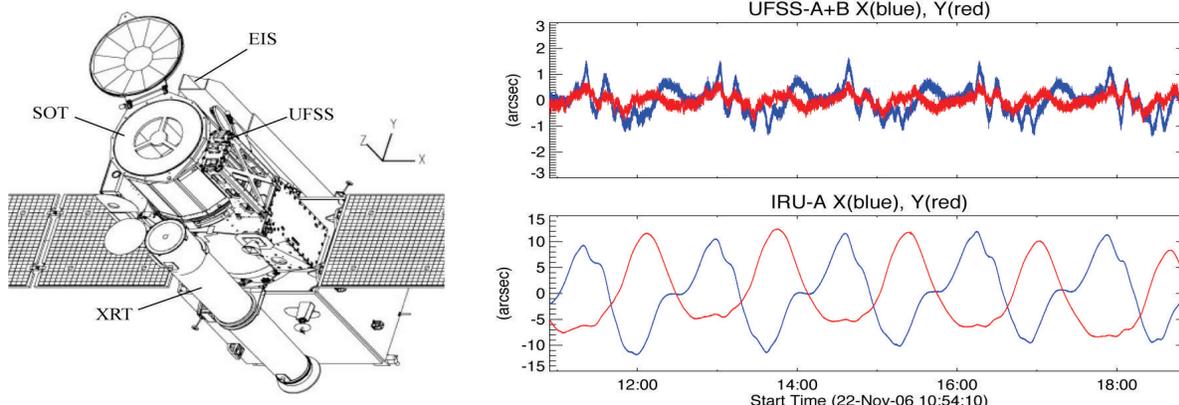
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### ABSTRACT

It is essential to achieve fine pointing stability in a space mission aiming for high resolution observations. In a future Japanese solar mission SOLAR-C, which is a successor of the HINODE (SOLAR-B) mission, we set targets of angular resolution better than 0.1 arcsec in the visible light and better than 0.2 - 0.5 arcsec in EUV and X-rays. These resolutions are twice to five times better than those of corresponding instruments onboard HINODE. To identify critical items to achieve the requirements of the pointing stability in SOLAR-C, we assessed in-flight performance of the pointing stability of HINODE that achieved the highest pointing stability in Japanese space missions. We realized that one of the critical items that have to be improved in SOLAR-C is performance of the attitude stability near the upper limit of the frequency range of the attitude control system. The stability of 0.1 arcsec ( $3\sigma$ ) is required in the EUV and X-ray telescopes of SOLAR-C while the HINODE performance is slightly worse than the requirement. The visible light telescope of HINODE is equipped with an image stabilization system inside the telescope, which achieved the stability of 0.03 arcsec ( $3\sigma$ ) by suppressing the attitude jitter in the frequency range lower than 10 Hz. For further improvement, it is expected to suppress disturbances induced by resonance between the telescope structures and disturbances of momentum wheels and mechanical gyros in the frequency range higher than 100 Hz.

### I. INTRODUCTION

HINODE (Solar-B) is a spacecraft dedicated to observations of the Sun, which was developed by the Institute of Space and Astronautical Science (ISAS) of Japan Aerospace Exploration Agency (JAXA), collaborating with National Astronomical Observatory of Japan (NAOJ) as domestic partner, NASA in United States and STFC in United Kingdom as international partners [1]. There are three telescopes onboard the spacecraft (Fig. 1). The Solar Optical Telescope (SOT), which has the largest aperture among the space telescopes for solar observations ever launched, and is able to measure the properties of magnetic fields and their dynamics precisely at the photospheric and chromospheric layers with the resolution of 0.2 – 0.3 arcsec [2]. The EUV Imaging Spectrometer (EIS) and the X-Ray telescope (XRT) have a capability to diagnose response of the solar outer atmosphere to magnetic field changes in the extreme UV and soft X-ray wavelengths [3][4]. Since the successful launch on 22 September 2006 (UT) with the JAXA's M-V rocket and installation to the sun-synchronous polar orbit of about 680 km altitude with a 98 min orbital period, the three instruments have provided surprising solar images to us.



**Fig. 1.** Drawing of the HINODE spacecraft with the definition of the coordinate axis (*left*), where Z-axis is pointed to the Sun and Y-axis is aligned to the solar rotation axis, and examples of time series of pointing errors measured with UFSS and IRU (*right*).

The good performance of the spatial resolution in HINODE is achieved by an attitude control system consisting of an ultra-fine sun sensor (UFSS) and mechanical gyros (inertia reference unit, IRU) as attitude sensors and momentum wheels (MWs) and magnetic torquers as attitude actuators [1]. Since the pointing requirement for SOT is much higher than that for the other two telescopes as is shown in Table 1, SOT is equipped with an image stabilization system employing a correlation tracker and a tip-tilt mirror (CTM) [5]. While the attitude control system control the spacecraft attitude in the frequency range lower than  $10^{-1}$  Hz, the SOT/CTM reduces the jitter in the frequency range lower than 10 Hz.

The attitude control system of the spacecraft and the image stabilization system equipped with SOT have made significant contributions to excellent findings during the past 4 years after the launch. In this paper, we evaluate the pointing stability of HINODE using the spectral analysis on the telemetry data, and summarize on-orbit performance of the pointing stability in comparison with the requirements for its mission instruments (Table 1). We mainly focus on the pointing stability around X- and Y-axes (see Figure 1 for the definition of the axes). We also compare the performance with the requirements on the pointing stability in the future Japanese solar mission SOLAR-C to identify critical items to achieve them.

**Table 1.** Requirements on the pointing stability of the mission instruments aboard HINODE.

Instruments	Time	Requirements (X/Y)	Unit
SOT	10 sec	0.09	arcsec $3\sigma$
	1 hour	2	arcsec 0-p
	Mission life	20	arcsec 0-p
XRT	1sec	0.7	arcsec $3\sigma$
	1 min	1.7	arcsec $3\sigma$
	1 hour	16	arcsec 0-p
	Mission life	32	arcsec 0-p
EIS	2 sec	0.6	arcsec $3\sigma$
	20 sec	1.1	arcsec $3\sigma$
	1 min	1.7	arcsec $3\sigma$
	10 min	2.0	arcsec 0-p
	1 hour	5.0	arcsec 0-p
	Mission life	50	arcsec 0-p

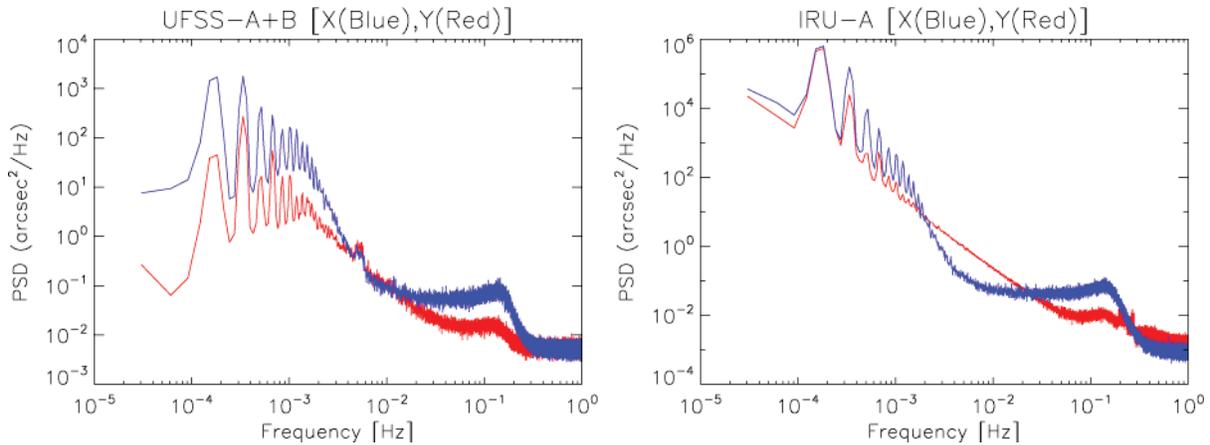
## II. POINTING STABILITY IN THE LOW FREQUENCY DOMAIN

The UFSS is developed to accurately measure the direction of the Sun to achieve fine pointing requirements in HINODE. It has attained the excellent performance, in which pointing signals with the random noise better than 1 arcsec ( $3\sigma$ ) and the bias noise better than 1 arcsec (0-p) in a field-of-view with  $\pm 0.5$  degree [6][7]. The HINODE satellite carries two identical UFSSs, UFSS-A and UFSS-B, for redundancy. The arithmetic average of pointing signals measured with UFSS-A and -B is used in controlling the spacecraft attitude in a normal operation mode. The IRU is inertial sensor using mechanical gyroscopes to detect changes of the spacecraft attitude with time. The IRU comprises two different kinds of gyroscopes: IRU-A is floated rate integrating gyro (FRIG) for primary usage in the attitude control system while IRU-B is a tuned dry gyro (TDG) for back-up. Since the IRU is sensing angular velocity, the time-integrated value of the IRU signals is used as the pointing error signals in this analysis.

On-orbit performance of the attitude control system is evaluated using spectral analysis on telemetry data taken with UFSS and IRU-A. In this analysis, we select 48 sets of the telemetry data with 0.5 sec sampling taken when the satellite is continuously pointing to the solar disk center longer than 6 hours in the periods without affected by the eclipse from November 2006 to March 2010. Examples of the telemetry data retrieved with UFSS and IRU are shown in Fig. 1 (*right*). It is clearly seen in the plots that fluctuation with the orbital period of about 98 minutes is dominant in the overall behaviour while higher frequency fluctuation is also visible.

A Fourier transform method provides us spectral characteristics of the pointing signal and major sources of disturbances hidden in the telemetry data. Figure 2 (*left*) shows power spectrum densities (PSDs, in a unit of  $\text{arcsec}^2/\text{Hz}$ ) for the pointing signals of UFSS, which are created by averaging PSDs derived in each time series. In the range between  $10^{-5}$  Hz and  $10^{-3}$  Hz, there are lots of peaks visible in the power spectrum, which correspond to the orbital modulation of pointing errors with the period of 98 minutes. The orbital modulation has a significant difference in the amplitudes of PSDs around X- and Y-axes. The orbital modulation is mainly

caused by thermal deformation of structures supporting UFSS and telescopes, which causes misalignment between the attitude control system and the telescopes. The contribution from the orbital modulation to the pointing error is about 0.6 arcsec (0-p) by integrating the PSD in the frequency range between  $8 \times 10^{-5}$  Hz and  $2 \times 10^{-3}$  Hz.



**Fig. 2.** Power spectrum densities of the pointing error signals measured with UFSS (*left*) and IRU (*right*).

In addition to the features related to the orbital modulation, the PSD has a smooth hump around 0.1 Hz, which is more significant in X-axis. The pointing stability due to the hump around 0.1 Hz is evaluated as about 0.1 arcsec (0-p) by integrating the PSD over the frequency range between  $10^{-2}$  Hz and  $2 \times 10^{-1}$  Hz. The frequency of 0.1 Hz corresponds to the upper limit of controllable frequency of the attitude control system. We will discuss the issue on the hump at 0.1 Hz later in Section IV. The small peak at  $5 \times 10^{-3}$  Hz does not have a remarkable contribution to the pointing stability.

Figure 2 (*right*) shows PSD of the pointing signals of IRU-A, which is again created by averaging PSDs derived in each time series. The PSD exhibits that the orbital modulation is predominant in the frequency range between  $10^{-5}$  Hz and  $10^{-3}$  Hz though its amplitude is bigger than in UFSS because of an effect of gyro drift. We thus focus on the pointing error only in the range between  $10^{-2}$  Hz and 1 Hz for the IRU hereafter. The smooth hump at 0.1 Hz is visible in the PSDs for the pointing signal of the IRU. This is a common feature in the PSDs for both the IRU and the UFSS. The contribution from the hump at 0.1 Hz can be evaluated as about 0.1 arcsec (0-p) in X-axis, which is also consistent with the value in UFSS.

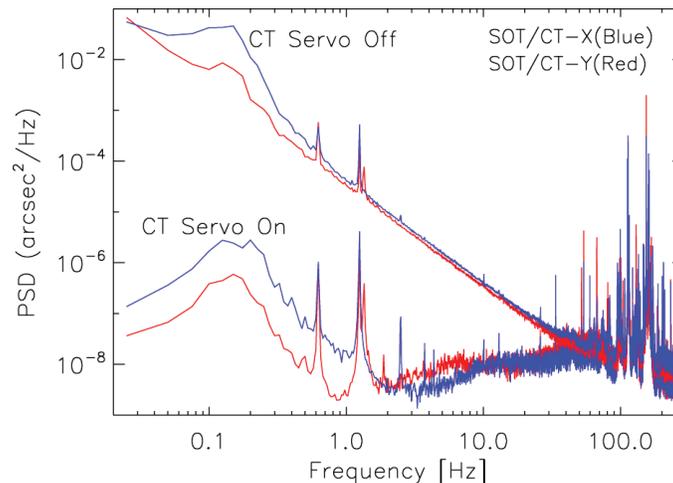
### III. POINTING STABILITY IN THE HIGH FREQUENCY DOMAIN

The CTM for image stabilization in SOT consists of a correlation tracker (CT) and a piezo-driven tip-tilt mirror with servo control electronics [5]. The CT uses a high-speed (580 Hz) CCD camera to obtain a displacement error with correlation tracking of solar granular motion. The displacement of the live images with respect to the reference image, updated in a specified interval, is estimated and then the derived jitter signal is fed to the closed-loop controller. The system suppresses displacement among images at frequencies lower than the crossover frequency of 14 Hz. It has been confirmed that the image stabilization system achieves a pointing stability of better than 0.03 arcsec ( $3 \sigma$ ) on orbit [5].

Because of the fast readout of the CT, pointing error signals retrieved with CT are useful to investigate the pointing stability in the frequency range higher than 10 Hz. Note that the Nyquist frequency is 290 Hz because of the sampling rate of 580 Hz. Figure 3 shows PSDs of the pointing error signals retrieved with CT in the cases of servo-on and of servo-off. The PSDs clearly show that the CTM successfully suppresses the attitude jitter in the lower frequency range lower than 20 Hz when the closed-loop servo is turned on. There is the significant hump at around 0.1 Hz, whose contribution to the pointing stability is about 0.06 arcsec (0-p) in X-axis. The feature is almost the same as in UFSS and IRU.

A lot of peaks are identified in the frequency range higher than 100 Hz, and which would be excited by resonance between telescope structures and external disturbance torques. Remarkable peaks at 113 Hz and 155 Hz in the PSDs are generated by the mechanical gyros (IRU-A and IRU-B). Other peaks are mainly due to the

disturbances induced by the MWs. The pointing error contributed from the high frequency peaks is higher than 0.01 arcsec (0-p) if we integrate all the peaks in the PSDs.



**Fig. 3.** Power spectrum densities of the pointing error signals measured with the CT in SOT.

#### IV. SUMMARY: COMPARISON WITH THE REQUIREMENTS IN HINODE AND SOLAR-C

We assess the on-orbit performance of the pointing stability with respect to its requirement by combining the spectrum analysis of the telemetry data taken with UFSS, IRU, and CT. Note that the pointing error is calculated by integrating the PSDs in frequency space of interest. We here use the pointing error only around X-axis as an example here because pointing stability is generally worse in the axis. Figure 4 (*left*) summarizes the on-orbit pointing stability thus evaluated with the requirements for the three scientific telescopes aboard HINODE. The systematic approach to achieve the requirements in HINODE is described in [8], which consists of analyses of the pointing requirements and performance in the frequency domain. It is found that the attitude control system onboard HINODE deliver better performance than the pointing stability requirements in the frequency range lower than 0.1 Hz. It is important to note that, without the image stabilization system, it is difficult to realize the good spatial resolution with SOT because the pointing stability of 0.1 arcsec (0-p) at 0.1 Hz achieved with the attitude control system is worse than the requirements of SOT. The image stabilization system with CTM has a crucial role on the reduction of the attitude jitter in the frequency range between  $10^{-2}$  Hz and 10 Hz.

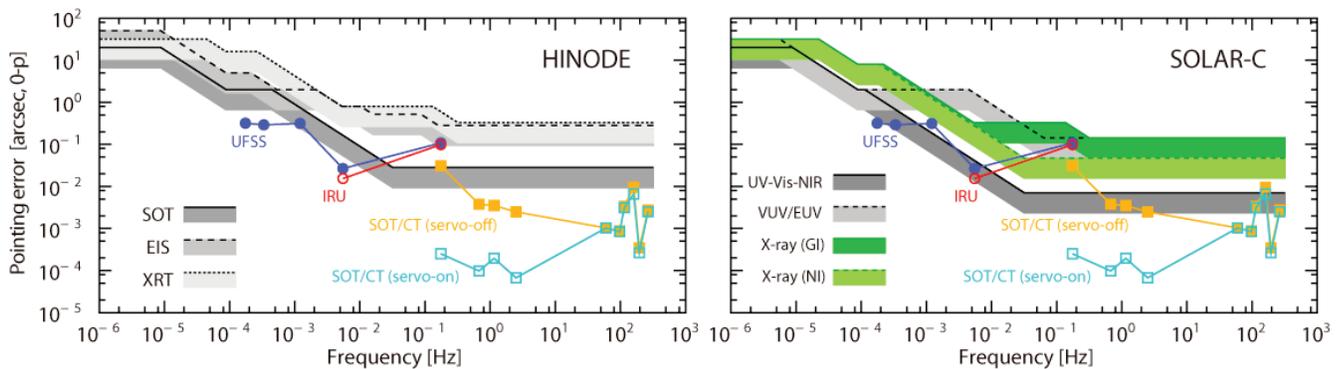
It is important to identify critical items to achieve higher pointing stability in the future solar mission SOLAR-C by comparing the achievements in HINODE with requirements in SOLAR-C. We set targets of angular resolution better than 0.1 arcsec in the visible light and better than 0.2 - 0.5 arcsec in EUV and X-rays. The requirements on the pointing stability are summarized in Table 2 and Fig. 4 (*right*). It is clear that the degradation in the pointing stability at 0.1 Hz does not meet the requirements of SOLAR-C. As is suggested from Fig. 2 and Fig. 3, the hump around 0.1 Hz is visible in all the PSDs derived from the telemetry data taken with UFSS, IRU, and CT, and its amplitude is more or less the same. This implies that the hump is not due to characteristics of the sensors, but should be induced by vibration of the spacecraft itself at that frequency. Because the transfer function of the attitude control system was designed not to have this kind of overshoots near the upper limit of the controllable frequency, the behavior around 0.1 Hz revealed in this analysis is slightly deviated from our expectation. One possibility is that the overshoot may be induced when there is a significant crosstalk of disturbances from Z-axis to X- and Y-axes. Since requirements on the pointing stability around Z-axis are less severe compared with those around X- and Y-axes, the pointing stability in Z-axis is generally worse than that in X- and Y-axes, which may be a cause of the peak around 0.1 Hz in the transfer function. This should be an important feedback to realize a space telescope with higher pointing stability without an image stabilization system.

It is also clear that the disturbances at the frequencies higher than 100 Hz have to be suppressed to achieve the resolution of 0.1 arcsec in SOLAR-C. Because the image stabilization system with CTM aboard HINODE is not effective to such high-frequency ( $>20$  Hz) disturbances, one possible approach is to improve CTM to have a broader response in the frequency as high as 200 Hz to suppress them. A camera with faster readout is essential to do it. The other approach is to suppress generation or transmission of the disturbances from MWs and the

mechanical gyroscopes, which is technically possible if MWs are mounted on a vibration isolation bench or we replace the mechanical gyroscopes with disturbance-free ones like fibre optic gyroscope (FOG).

**Table 2.** Requirements on the pointing stability of the mission instruments aboard SOLAR-C.

Instruments		Time	Requirements (X/Y)	Unit
UV-Vis-NIR telescope		1 sec	0.015	arcsec $3\sigma$
		10 sec	0.015	arcsec $3\sigma$
		1 hour	2	arcsec 0-p
		Mission life	20	arcsec 0-p
VUV/EUV imaging spectrometer		0.5 sec	0.3	arcsec $3\sigma$
		5 sec	0.3	arcsec $3\sigma$
		1 hour	2	arcsec 0-p
		Mission life	32	arcsec 0-p
X-ray imaging	Normal incidence	1 sec	0.1	arcsec $3\sigma$
		10 sec	0.1	arcsec $3\sigma$
	Grazing incidence	1 sec	0.3	arcsec $3\sigma$
		1 min	0.7	arcsec $3\sigma$
		1 hour	8	arcsec 0-p
		Mission life	32	arcsec 0-p



**Fig. 4.** On-orbit performance of the pointing stability in HINODE in comparison with the requirements for the scientific telescopes aboard HINODE (*left*) and SOLAR-C (*right*). The thick, dashed and dotted lines represent the requirements as a function of frequencies while the lower boundaries of the shaded belts indicate conditionally acceptable level, which is defined as one third of the requirements. The blue filled circles show the pointing stability evaluated with UFSS, the red open circles are that with IRU. The open cyan squares indicate the pointing stability evaluated with CT in the case of servo-on, and filled orange squares are that in the case of servo-off.

REFERENCES

- [1] T. Kosugi, et al., "The Hinode (Solar-B) Mission: An Overview," *Solar Physics*, vol. 243, pp. 3-17, June 2007.
- [2] S. Tsuneta et al., "The Solar Optical Telescope for the Hinode Mission: An Overview," *Solar Physics*, vol. 249, pp. 167-196, June 2008.
- [3] J. L. Culhane et al., "The EUV Imaging Spectrometer for Hinode," *Solar Physics*, vol. 243, pp. 19-61, June 2007.
- [4] L. Golub et al., "The X-Ray Telescope (XRT) for the Hinode Mission," *Solar Physics*, vol. 243, pp. 63-86, June 2007.
- [5] T. Shimizu et al., "Image Stabilization System for Hinode (Solar-B) Solar Optical Telescope," *Solar Physics*, vol. 249, pp. 221-232, June 2008.
- [6] M. Kubo et al., "Performance Verification of Ultra Fine Sun Sensors (UFSS) aboard HINODE," *JAXA Research and Development Report*, vol. RR-07-013, pp. 1-13, Feb. 2008.
- [7] K. Tsuno, T. Yamamoto, M. Kubo, T. Shimizu, E. Hirokawa, T. Hashimoto, "CCD Sun Sensors on board "HINODE" Solar Observatory," *Proceedings ICSO 2008*, Oct. 2008.
- [8] N. Yoshida, et al., "Systematic Approach to Achieve Fine Pointing Requirement of SOLAR-B," *IFAC ACA2004*, pp. 101- 106, June 2004.